ELECTRIFICATION IN INDUSTRIAL REVOLUTION 4.0

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ABSTRACT
The article outlines new approaches to managing electrification that are driven by a radical transformation of scientific, technological, environmental, and economic conditions. These include spreading the use of electromechanical devices following the onset of a digital economy, the creation of highly efficient, small-scale power-generating units and lower cost of energy from renewable sources, wider economic collaboration between energy suppliers and consumers based on demand–response mechanisms, and stricter environmental regulations. The article defines the characteristics and trends of the new phase of electrification, assesses its contribution to economic growth and the environmental security of a region, and offers recommendations as to the optimization of the technological structure of the electric power industry in view of evolving requirements for greater reliability, environmental friendliness, and service support of power supply.

The authors bring out the principles of the provision of electricity to households in smart cities and identify the main areas of focus for increasing the economic efficiency of adopting innovative electrical technologies through a balance of national economic and business interests. A methodological toolkit has been designed for measuring the level of electrification in a region.
Keywords: demand-side management, electrical technology, electrification, industrial revolution, intelligent manufacturing, smart city, technological modernization.

1 INTRODUCTION

New manufacturing technologies that have been developing rapidly under the influence of the ongoing Industrial Revolution 4.0 will call for a significant change in the energy consumption balance toward electricity and for tougher standards applied to energy quality and reliability of supply [1, 2]. By 2025, global energy consumption is projected to grow by 60%; it will double by 2050 compared to 2010, growing at a much faster pace than the overall demand for fuel and energy [3].

In this context, the International Electrotechnical Commission (IEC) [4] names smart electrification a fundamental factor of energy sustainability under the conditions of the industrial revolution as it implies sensible and efficient usage of electricity as the main source of energy. This is due to electricity being the most universal and easy-to-control type of energy that is consumed practically at loss-free by the end consumer; it does little harm to the environment and can be generated using modern green technology.

'The electrical world' is strikingly versatile. It encompasses 'smart' energy-efficient homes that are equipped with an assortment of appliances for domestic comfort, many of which have internal sources of energy, including micro-batteries. The share of the newest electrochemical and electro-physical appliances that were designed on the principles of bio-resonance or amplifiers of various types is growing [5]. The adoption of electricity qualitatively improves indicators of energy usage in domestic and industrial heating, ventilation, and air conditioning (HVAC) systems, primarily because the distribution of the used energy over time and its volume can be controlled in a smart way and facilitates cost reduction. Electricity opens up colossal opportunities for 'green' energy production and energy consumption in the field of electric transport, potentially resulting in a considerable reduction of greenhouse gases [6]. Conventional and hi-tech industries would benefit, too. Recent advances in electrochemistry, along with nanotechnologies make it possible to create new materials and construction with

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pre-set structural, mechanical, and physical properties. Solar concentrators can be used for obtaining high melting point materials by means of high-frequency currents. Thin coatings can be applied on materials by specialized electrochemical electrolytic units instead of conventional electroplating installations.

The new phase of electrification plays a critical role in smart city engineering as energy, heating, gas, and water supply systems and telecommunication structures in it merge into 'a system of systems' that requires new approaches to dispatch control [7]. A smart city typically favors green energy derived from renewable sources, passive houses and commercial facilities with practically zero energy consumption, or active houses that generate and accumulate electricity by means of solar panels and off-grid fuel and energy systems [8].

Researchers point to some peculiarities in the current phase of electrification that stem from changes in the structure of energy technologies, stricter standards for reliability of power supply due to growing integration of critical infrastructures, and the emergence of tools that make it possible to analyze energy consumption over a time period and to respond flexibly to demand [9–11]. This study aims to identify these typical peculiarities, to design a methodological framework for planning and managing the new phase of electrification, and to suggest a panorama of theoretical and applied research on the subject.

2 ELECTRIFICATION PATTERNS

The authors define electrification as the process of adoption of efficient electrical technologies by various industries. The process is unlike anything else as it occurs in phases and is discrete: each phase is different due to the different structures of electrical technologies being adopted and the objects they are applied to. When there is a pause between the phases, individual types of electrical technology are occasionally deployed in certain industries.

Electrification as a process is determined by essential features such as: higher utilization of energy at a general economic and industrial level; growth in the average energy intensity of production (services) that can decrease during a pause between the phases of electrification; and the number of newly launched generating and transmission installations grows ahead of or in line with the growing load.

There is a limit to how vastly electricity can be adopted, which is indicated by the share of electricity in the structure of energy carriers at each phase due to resource and economic constraints. A drop in energy intensity between two consecutive phases of electrification occurs because new technologies with better energy efficiency characteristics are embraced.

2.1 Electrification and technological progress: structure of electrical technologies

Any technology is based on a certain type of useful energy that is derived from various energy carriers. Among all of them, electricity is the most efficient energy carrier that delivers a unique improvement in the outcomes of technological processes from the point of view of energy, economy, environment, and social development. This means that all promising technological innovations are essentially electrical technologies. As these technologies constitute the material substance of electrification as a process, the latter should be viewed as the most progressive and universal energy form of technological progress [12].

Structurally, electrical technologies vary by industry as well as by their functionality; in the latter case, they can be viewed as sector non-specific. It is useful to group such technologies into: (1) those replacing traditional technological processes and (2) brand new ones as to

Table 1: Forms of electrification.

Form	Mass	Local
Distinctive features	Triggered by revolutionary advances in technology Occurs across industries An economic and social efficiency leap is observed Low or medium energy intensity of equipment The timeline of the process is determined by electricity saturation limits of industries converting to electricity Government involvement is required at the initial stage	Progress of electrification is restricted by economic and structural factors The process is 'stretched' over time Technological innovations are implemented in a competitive business environment
Types	1. Primary – use of electricity for lighting and powering machines 2. Electricity is adapted for the majority of energy-consuming processes in households, commercial and manufacturing industries 3. New phase – 'cybernetic' electrification	1. Competitive • The choice is between 'electricity' and 'fuel' • Key criteria: price comparison (electricity vs. natural gas; electricity vs. oil fuel), per unit cost of electricity, financial and investment capabilities of consumers, pressure of competition, environmental requirements 2. Monopolistic • Electricity serves as the only possible energy carrier for production or manufacturing processes • Main constraint – production structure of processing industries that is highly inert

their functions and performance. The process of electrification as such can take one of two shapes: mass electrification and local electrification (Table 1).

Primary mass electrification helped create a developing power engineering infrastructure (power plants and grids) that later drove quick adoption of telecommunication and radio electronics of various designations (radio and television, computers, cell phones, and satellite communications). These are low-power devices, but the current scale of their application generates a considerable load on the electric power industry.

Local electrification means the adoption of cutting-edge electrical technologies only by a number of companies for specific processes. One needs to observe that in the case of local electrification, electricity-powered systems are launched at a slower or at best at the same pace as machines powered by other fuel alternatives. An acceleration of the deployment of electricity-consuming equipment is the first sign of the start of mass electrification and the gradual phasing out of traditional technologies. Local electrification can, therefore, grow into mass electrification if the conditions are right.

It is worth noting that the types of local electrification indicated in Table 1 are notable due to the high energy intensity of production and a relatively high cost of equipment.

Mass electrification was propped up by economic growth, a big wave of simultaneously emerging electrical technologies, and the development of the electric power industry on the basis of large thermal and nuclear power plants. The future progress of electrification will probably be of local nature and take the shape of an individual discrete process. This will result in growing uncertainty as regards the development of the industry and can be mitigated through the development of small-scale, high-flexibility power generation systems and mechanisms of demand-side management.

There are prospects for local electrification in the electric vehicle sector and unmanned transport, full home automation ('smart homes'), and a transition to a new phase of robotization with elements of AI in manufacturing.

The driving forces of these essentially revolutionary innovations are the cutting-edge technical solutions that are appearing in the fields of energy conservation, reliability and safety, cost reduction, and simultaneously growing per unit capacity of equipment. Low-to-medium power electrical technologies and equipment (in the range of hundreds of kW h per manufactured unit) will experience a massive progress as electrification in them becomes a source of extremely high efficiency or improves working conditions. Energy-intensive electrical technologies (in the range of thousands of kW h per manufactured unit) will be predominately used where there is no fuel alternative to electricity (e.g. production of some materials in metallurgical and chemical industries) or when products are required to have specific properties (e.g. electrical, physical, and chemical processes in metalworking).

The future progress of electrification will be largely determined by economic recovery and price competition between alternative energy carriers, e.g. electricity and natural gas. In this context, it might be appropriate to raise the issue of finding a more effective application for high-quality fuels.

2.2 Factors of electrification

Electrification is driven by a balance of national economic interests (pursued by government) and commercial interests of businesses. National economic interests are manifested in the state's economic policy that is aimed at achieving innovation-driven (resource-effective) economic growth and considerably improving the technological standing of the national economy as a whole.

Businesses are interested in reducing the production costs, increasing productivity and expanding production capacity, and achieving a better quality of products, which will provide them with a competitive edge on domestic and foreign markets and eventually boost their financial performance.

Businesses can be motivated toward electrification by:

- cost and quality competition (external and internal),
- government-provided incentives for adoption of cutting-edge electrical technologies, and
- government-provided incentives for energy conservation by consumers.

It is extremely important to show to the business sector that electrification is commercially effective as it ensures the following:

1. productivity growth (intensification of production, reduction in staff number as a result of automation policy),

2. lower cost of production (as a result of price differences of fuel and electric power),
3. higher quality of products (precision of control over technological processes and strict adherence to parameters),
4. automation and cybernetization of manufacturing (with an option of parameter fine tuning in line with technical as well as economic criteria, considering the fact that in an advanced market, the price of electricity can change virtually every minute),
5. the small size of electricity-powered machines (e.g. an electric furnace is 30% smaller than a blast furnace of the same capacity),
6. better workplace safety and comfort, and
7. reduction of economic impact on the environment.

The key factor of the economic effect of electrification is the cost of electricity, or rather how it compares to the cost of alternative energy carriers. This factor is particularly critical in the case of district power supply. As noted in [13], it is essential to take into account both the cost of consumed electricity and the associated costs of manufacturing operations that use electrical technologies. An indicator of the commercial effect in that case might be the elasticity of the substitution of electricity.

To measure the efficiency of electrification, a company must use the maximum marginal price that matches the manufacturing profitability target that ensures the company's competitiveness and satisfies the owners' interests. This price is reported to the regional electrification administration, and an average price of electricity is determined based on the information from all local companies. The figure serves as a benchmark for the region's technological policy in the field of power engineering (unit output, types of power plants, their location, types of primary energy resources, layout of grids).

In some cases, the government will have to offer subsidies to energy companies as the average price of electricity may prove too low to keep them profitable. The optimum volume of power consumption that is delivered by the model is distributed among the companies according to their declared marginal prices based on the 'higher price–higher volume' principle.

Should there be a shortage of electricity, it can be compensated for by means of the following:

- in-house generation,
- energy conservation (through direct load control contracts), and
- adjustment of project parameters to make them less energy intensive.

2.3 Level of electrification

It is appropriate to speak about an optimum and a rational level of electrification. An optimum level is when the achieved rate of electrification delivers the maximum commercial and cumulative publicly useful economic effect that takes into account both the gross effect and the costs of the process. A model that makes it possible to determine the optimum level of electrification is presented in Fig. 1.

In the context of electrification management, the desired result is not to achieve the optimum level of electrification that is computed on the basis of a strictly deterministic yet abstract economic model, but a rational (effective) one.

A rational level of electrification is the result of identifying and coordinating the interests of government, corporate electricity consumers, and utilities. Whether the achieved level of electrification is rational is a factor of the effectiveness of motivational tools.

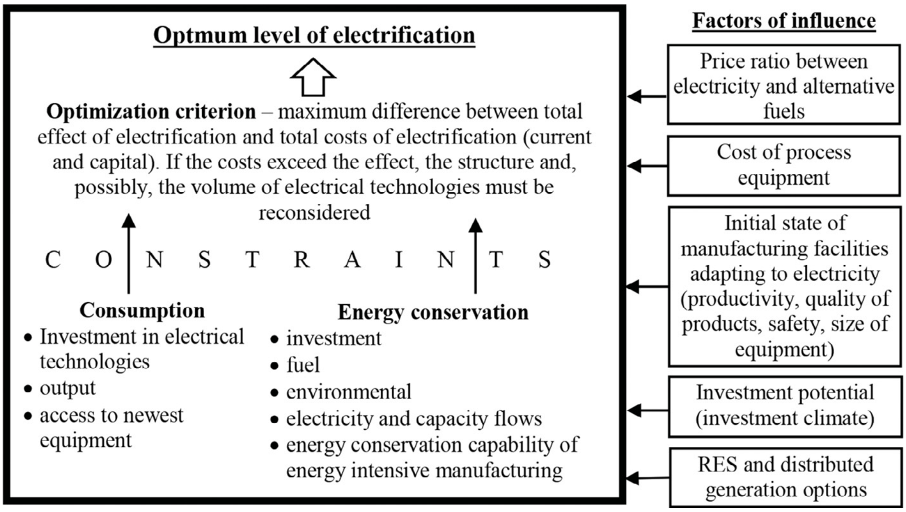

Figure 1: Model of optimum level of electrification of an economy.

The motivational toolkit includes a variety of methods of influencing the economic interests of the participants engaged in electrification: advertising and information support and transfer of advanced technologies, various financial incentives, demand response mechanisms, renovation of the structure of power-generating capacity, etc. The fundamental principle of rational electrification management is to encourage a combination of energy-saving and the newest electrical technologies that are aimed at reducing the load on the power engineering sector and at cutting prices of electricity.

This necessitates collaboration between consumers and suppliers within the framework of demand response programs (that should be promoted by government).

A strong motivational factor originates in a tense competitive business environment in terms of production costs and quality of products.

1. Control over electrification should be localized within one region (a unified energy system) as territories can differ significantly both in terms of demand for and the supply of electricity.
2. A factor worth mentioning is the transformation of energy systems toward distributed generation that increases the reliability of power supply and the efficiency of the adoption of electrical technologies.
3. An evaluation system needs to be elaborated for assessing the performance of the electrification management toolkit. The system would set reference points for making a conclusion about the rationality of the achieved level of electrification.
4. Considering the above, one can conclude that a rational level of electrification in a region is not a local characteristic, but a complex, comprehensive concept. In other words, if the recipients adequately take external control signals and the level of electrification grows, it can be deemed rational (at the time being).

To raise the level of electrification, the following key conditions must be met:

- economic growth of at least 4%–6%,;
- active price and quality competition among producers,

- motivating prices for electricity (capacity) and acceptable cost of new connections, and
- minimum constraints on connection of new consumers to the grid.

2.4 Government participation in electrification management

In practice, it is not always possible to ensure a balance of interests between government and business. The barriers to this include investment risks faced by businesses and the high cost of electricity in case of growing power intensity of production. This forces government to provide targeted incentives for the adoption of electrical technologies, such as the expansion of the country's export potential thanks to substitution of electricity for high-quality fuels in various industries, higher labor productivity amid a shortage of manpower, an improvement in living standards thanks to provision of power supply to households [14, 15].

The list of such incentives includes:

- price and tax regulation,
- investment (through acquisition of stakes in companies),
- subsidized loans (including interest-free loans),
- targeted R&D funding,
- import of the newest electrical technologies, and
- training for electrical technology professionals.

The objects of government administration are the two interacting parties – consumers and suppliers of electricity, that is, energy companies that generate and transport electricity. In this regard, it should be said that a reduction in price of electricity, thanks to technological advances of the electric power industry and optimization of the structure of generating capacity in energy systems, plays the most critical role in wider adoption of new electrical technologies and, therefore, results in lower costs of electrification management for the state.

A vivid example of government participation in electrification management is state support for renewable energy in various countries. Available support measures are usually of comprehensive nature, such as the development of a regional energy policy that incorporates various individual preferences in terms of technology and services, the introduction of feed-in tariffs, subsidies for consumers who opt for electricity as the ultimate energy carrier, monetary and tax support for manufacturers of energy-efficient equipment, and occasional assistance in design, installation, and launch of electrical equipment [16, 17].

3 NEW PHASE OF ELECTRIFICATION

This new phase that might be referred to as 'cybernetic' is characterized by the adoption of advanced power generation and grid technologies and the emergences of new organizational and economic mechanisms for collaboration among manufacturers, suppliers, and consumers (Table 2).

One of the most interesting manifestations of the new phase of electrification is the growth in portable power sources. A boom in portable power that we are witnessing today is an outcome of the mass adoption of various gadgets, monitoring and security systems, information and communication technologies, and mobile telecommunication devices. The total global battery capacity of the most popular portable devices – mobile phones and laptops – is about evenly divided between the two – 50 GW h of mobile phone batteries and 40–50 GW h of laptop battery capacity. Recharging them requires about 10–15 TW h a year. Smartphones with large screens are replacing outdated mobile phones, hence the need for larger battery

Table 2: Technological and organizational solutions for new phase of electrification.

Generation and transmission	**Consumption**	**Collaboration among producers, suppliers, and consumers of energy**
Knowledge-intensive electrical systems with automated, optimality guided load distribution capability Automated control over reliability and quality of power supply – control, regulation of electricity flows, and self-restorability Energy storage systems for RES Off-grid power supply installations and mobile generators	Electrification of auto transport and high-speed rail Knowledge-intensive technological innovations that made administrative decisions in the fields of energy use and energy consumption Automatic control devices (robots, sensors, servers) High-capacity accumulators for off-grid consumers Portable power solutions	Demand-side management Two-way real-time exchange of volume and price data Optimization of prices for electricity and capacity Mutual responsibility as regards reliability of power consumption (compensation of damage caused by disruption of schedule and irregular parameters)

capacity and higher electricity consumption. The spreading use of digital control systems with numerous intelligent sensors and operation mechanisms and the development of entertainment devices fitted with AR and VR technologies provide an additional impetus to portable power solutions [18].

At the same time, portable power devices with an output of a fraction of a watt to a few hundred watts is at the bottom of the power capacity hierarchy (Fig. 2). Technologically, portable power devices utilize a new generation of chemical sources of electric current, electrochemical accumulators, supercapacitors, and low-temperature hydrogen fuel cells. Work is in progress on methanol fuel cells.

Extremely high standards are imposed on electrical technologies that are being adopted at the new phase of electrification as regards the reliability of supply, observance of parameters, and construction and operation of on-site small- and medium-size generators. Equally high standards must be met by support and maintenance services that use multi-agent control

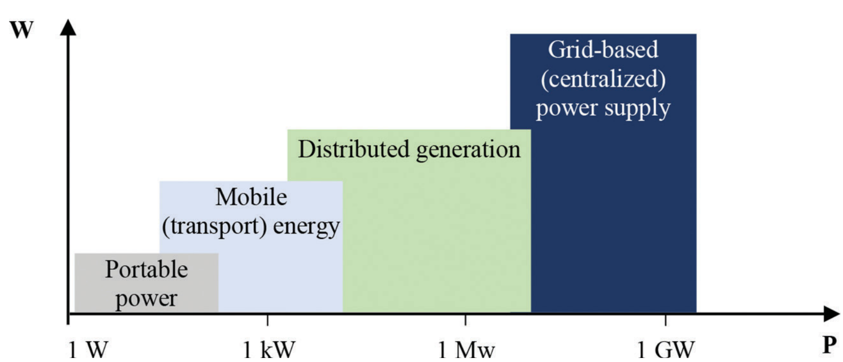

Figure 2: Unit capacity (P) of generators in various segments of electricity production and total volume of consumption (W) [19].

systems [20, 21]. This results in a wider range of internal and external services that find application in a region's energy sector:

- remote monitoring of equipment and engineering networks that is fused with asset management systems of utilities;
- customized load control, lighting, and building climate control;
- predictive risk-based maintenance of buildings; and
- procurement and logistics strategies of energy companies that are based on consumer demand forecasts [22].

At the new phase, the principles of electrification are stipulated by the evolution of external scientific, technical, technological, and economic conditions. This does not preclude compliance with groundwork conditions such as a friendly investment climate, an adequate financial system, and unrestricted access to technologies and financial resources in global markets. The list of the key principles includes the following:

- wide adoption of new electromechanical devices as part of the development of a digital economy in various industries, including households and organizations other than manufacturing;
- creation of competitive electricity and capacity markets;
- creation of high-performance small-size generators;
- reduction in cost of energy generated by alternative and renewable energy sources;
- government technical and economic regulation of the electric power industry using a combination of direct and indirect regulatory methods;
- greater scope of economic impact of suppliers and consumers of energy through demand-side management mechanisms;
- adoption of economic methods of power supply reliability management (accountability of supplier for disruptions in power supply, tariffs that vary by time and security of supply);
- broader cross-country diffusion of innovative electrical technologies;
- a greater number of potential investors and sources of investment in electrification; and
- tougher environmental restrictions on power engineering.

In general, electrification management at a regional, industrial, and consumer level follows a universal algorithm and covers several areas that are presented in Table 3.

4 A PANORAMA OF RESEARCH ON NEW PHASE OF ELECTRIFICATION

The new development conditions for electrification add to the relevance of the following research challenges:

- providing justification for priority areas of electrification on the basis of multiple criteria decision analysis;
- assessment of the potential contribution of electrification to economic growth;
- forecast of electricity intensity of GDP and of products (services) in specific industries;
- optimization of the technological structure of power engineering, considering the new requirements for reliability and environmental friendliness of power supply, cost of service ensuring timely management of spikes in peak load (differing by region);
- revision of the energy market model in view of the new requirements to be met by power engineering;

Table 3: Key areas of action in electrification management.

№	Area of action	Activities
1	Assessment of prospects for electrification	Assessment of the level of electrification, its economic and commercial performance. Identification of electrical technologies that should be given priority. Calculation of 'effective' cost of electricity. Identification of barriers to and design of incentives for electrification
2	Government-provided incentives for electrification	Introduction of price regulation, tax incentives, and targeted funding of electrification projects
3	Development of power engineering as foundation of electrification	Provision of sufficient capacity to meet load demand. Minimization of cost of power supply. Control over reliability of power supply (power supply continuity, quality parameters) and environmental sustainability of electricity generation
4	Search for additional resources for electrification in energy consumption	Proactive energy conservation in traditional electrical technologies. Substitution of quality fuel with electricity in manufacturing and at home
5	Demand-side management programs implemented by utilities	Development of concept and targeted demand response programs. Compilation of list of essential technical means. Creation of economic and administrative incentives for utilities and consumers to encourage their engagement in demand response programs. Development of institution of aggregators and energy services market

- improvement in electricity (capacity) rates by making them more variable, and thus boosting their motivational function;
- design of a multi-tier comprehensive economic mechanism of electrification management, considering the priorities of the national economy and based on the balance of interests of electricity suppliers and consumers; and
- development of groundwork for government's investment policy in the field of electrification and wide adoption of innovative electrical technologies.

The authors have identified the following promising areas of research in the field of electrification.

- Electrical technology: structure, application, functional and energy characteristics of new electrical technologies; factors restricting the development of new technologies; prospects of wider application of traditional electrical technologies
- Energy conservation and energy efficiency in energy consumption: possible areas and trends in energy conservation; energy-saving technologies and their energy and economic characteristics; rationalization of energy consumption schedules; organizational factors of energy conservation; methods of assessing the potential for energy efficiency

- Promotion of electrification and energy conservation: price and tax regulation; administrative methods (restrictions); mechanisms of market competition
- Power engineering and electrification: projected trends in energy intensity of production (services); technical and economic efficiency of power engineering (level evaluation, analysis of factors, methods of improvement); requirements for reliability of power generation and transmission (including continuity of power supply and quality parameters for energy carrier); forward-looking structural and technological transformation in the industry; broader collaboration between utilities and consumers (including demand–response programs)
- Fuel-related problems of electrification and investment issues: economic efficiency of fuel substitution with electricity (cross-sectoral approach); optimization of demand for investments in manufacturing and electricity consumption; optimization of the structure of sources of investment
- Issues of engineering and economic training of professionals in the field of electrification management (in various industries): formats of training, required competencies, corporate management audit

As a separate area, there is a series of consecutive research tasks that emerge along with the formation of systems of smart cities (Fig. 3).

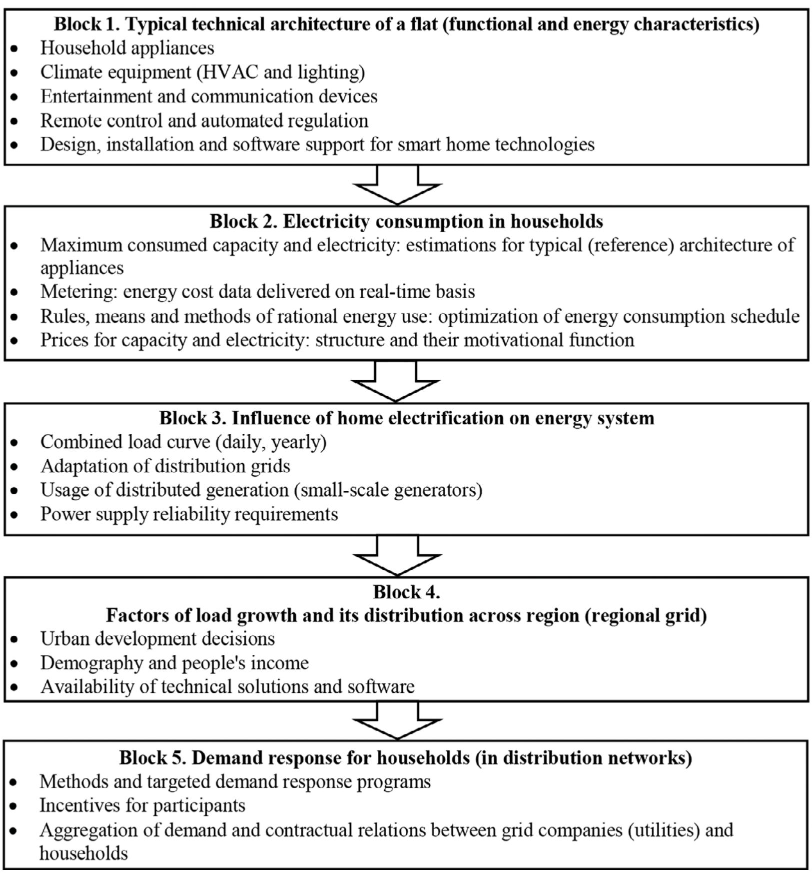

Figure 3: Home electrification–themed research.

5 CONCLUSION

At the foundation of Industrial Revolution 4.0 are radically new management systems, materials, production and transportation technologies that are often closely interconnected and, therefore, create a strong synergistic effect when applied together. Technological innovations penetrate all the economic sectors and radically change the structure of demand for energy and requirements for energy resources, with electricity taking the lead as the cleanest, most flexible, and controllable energy carrier.

The continuing electrification of manufacturing, transport, and homes, stronger demand segmentation with varying trends of demand volume and structure are among the critical outcomes of the industrial revolution from the energy sector perspective. Further segmentation is to be observed in the technological structure of the energy sector in pursuit of the most efficient satisfaction of future demand.

This study showed the complexity and comprehensive nature of the tasks and processes of the new phase of electrification. Implementation of this new phase will, of course, require coordinated efforts from government, energy business, vendors of research-intensive service solutions, and consumers, of whom a growing share is taking on a pro-active role. The significance of electrification today is indisputable. One obvious evidence is the Covid-19 pandemic that made the economies of all countries dependent on the reliability of virtual communication and various information technologies, which operationally depend entirely on electricity and electrical technologies. In this context, this article presents a number of theoretical and practical scientific findings that could contribute to effective organization and administration of the new phase of electrification. The panorama of priority research subjects suggested by the authors could spur the generation of new knowledge that would expand the idea of opportunities presented by electrification amid today's abundance of advances in science and technology.

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